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PROBLEM SOLVING INSTRUCTION FOR PHYSICS

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ABSTRACT

A domain-specific information processing model of problem solving behavior in elementary electrostatics was developed. Instruction based on this model was evaluated in a large university-level physics course. The experimental design utilized treatment and instructor as crossed factors. Dependent variables included a test of problem solving strategy comprehension, a test of problem solving skill, and a problem solving protocol score. Significant treatment group differences were found only for the comprehension test. Parallels between the content of the experimental treatment and (a) an instructor effect in the skill measure, and (b) an ability effect in the protocol measure, support the validity of the model developed.

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THE PROBLEM

Typically, the instructional activity in introductory physics is centered around weekly lecture and recitation sessions. The lectures emphasize rigorous development and demonstration of pertinent concepts, while the recitation sessions are usually devoted to solving physics problems. The understanding that typical examinations test frequently requires an integration of the concepts and problem solving skills treated in lecture and recitation sessions. However, instruction developing this problem solving resilience is not ordinarily an explicitly developed component of instructional activity.

Using current understanding of problem solving processes resultant from psychological research, instructional materials were designed to bring the instructional activities in a typical physics course more in line with the expected learning outcomes. The topic of electrostatics was chosen, at the level of introductory university physics with calculus. This choice was motivated by the following reasons: to focus on a topic with which students have particular difficulty, to avoid topics to which students may bring inaccurate preconceptions, and in order to limit the scope of this project.

APPROACH

Goal of Instruction

The following is suggested as an explicit goal of instruction in electrostatics: the student shall be able to apply the concepts of

electrostatics to a variety of physical situations in which the relationships between these concepts need to be developed or made explicit.

The materials developed for this study addressed a limited range of this goal. First, they focused exclusively on what are considered to be the three central concepts in electrostatics: charge and charge distribution, electric field, and electric potential. The concepts of energy content of an electric field, capacitance and dielectrics are second order concepts dependant on the concepts of charge, field, and potential and were not treated. Second, the instruction was restricted to physical situations falling entirely within the domain of electrostatics. Situations involving the "embedding" of electrostatics concepts within the domain of kinematics were not addressed.

The instruction was not limited, however, in the geometries typically treated in elementary electrostatics. These include: the point, simple distributions of several points, lines and pairs of parallel lines, planes and parallel planes, spheres and spherical shells (concentric and side by side), concentric cylindrical shells, disks, and rings.

Theoretical Framework

The theory upon which the instruction was based is a restatement of modern cognitive theory of problem solving in the tradition of information processing psychology (Chi & Glaser, 1979, 1980; Greeno, 1976a, 1976b, 1977; Hinsley, Hayes & Simon, 1976; Larkin, 1979a, 1979b,

1980b; Larkin, McDermott, Simon & Simon, 1979a, 1979b, 1980; Mayer, 1974, 1980; Mayer & Greeno, 1972, 1975; Mayer, Stiehl & Greeno, 1975; Newell & Simon, 1972). Problem solving, in this tradition, is characterized as understanding and search (Polson & Jeffries, 1980). Expert "understanding" in physics problem solving involves the use of a qualitative scientific representation of the phenomena at hand as a guide to the selection of a method of solution (Chi, Feltovich, & Glaser, 1980; Greeno, 1980; Larkin, 1980a). "Search," therefore, has the character of knowledge development, building toward a goal, rather than of means-ends analysis, working backwards from a goal.

A problem solver, when faced with a problem, has a representation in memory to which he or she fits the problem. Depending upon the degree of meaningfulness of that fit, the solver then brings to bear a number of search processes which act upon the representation, elaborating or instantiating a path to a solution. Depending upon the degree of meaningfulness inherent in the representation to which the solver fits the problem, the search may be straightforward or it may be circuitous; a solution may result forthwith, or it may elude the solver entirely.

It is important to note that the representation (also termed cognitive structure or schema) brought to bear on the problem is an organized collection of experience with this and similar problems. Thus, problem solving is knowledge-dependent or knowledge-based. Skill in problem solving is not reducible to a general procedural skill alone. Rather, it is in part determined by a large body of organized knowledge

structured for the purposes of solving problems in a particular domain, and in part determined by a set of possibly quite specific concomitant rules, procedures, or heuristics which act upon that knowledge.

In the context of this explicit theory of problem solving, then, is the hypothesis that within the range of this study's restricted goal of instruction there exists, for persons with the target problem solving competency, one core electrostatics schema. A schema is a representation in memory into which new information is assimilated. As such, schemata (in particular, schemata for the core area of electrostatics) will vary from individual to individual. But, it is assumed that this variation converges on what is characterized as one core schema as expertise approaches the level of competency specified by the instructional goal.

Also it is assumed that: this electrostatics schema has a specifiable structure; the development of this schema within the memory of the student is the immediate goal of instruction; this schema, at the level of elementary electrostatics, is comprehensible to novices; and finally, it is possible to teach this cognitive structure to students.

Also, in the context of the explicit problem solving theory, it is hypothesized that there is an identifiable and instructable set of mental procedures or problem solving strategies which enable one to apply the elctrostatics schema to a given situation irrespective of any stated problem solving goal based on that situation.

A pilot study was conducted in which eight subjects addressed several open-ended electrostatics situations, while concurrently

thinking out loud. Based on transcripts of the thinking out loud protocols, and guided by cognitive theories of problem solving, a schema for electrostatics and a set of procedural behaviors which utilize it were identified.

Description of the Core Schema

The core schema is not a general declarative exposition of electrostatics (e.g., what is in a textbook). Rather, it is an exhaustive list of what one might say about any given situation. This list is represented in question format in Table I. A pictorial representation of the essential concepts and relationships of the core schema is presented in Figure 1.

The core schema included a qualitative level and a quantitative level for each of the three concepts: charge and charge distribution, electric field, and electric potential. These levels correspond to the "scientific" (qualitative) and "mathematical" (quantitative) levels of representation employed by expert problem solvers (see Larkin, 1980a).

At the qualitative level, attention is focused on such things as: possible cases, limiting cases, useful approximations, points of interest, geometrical descriptions, and application of qualitative aspects of principles or relations. For example, given a situation involving two point charges, one would state, at the qualitative level, that the principle of superposition applies in determining the resultant electric field at any point in space. A vector-sum diagram for one point in space may be drawn as a pictorial representation of the principle.

TABLE I

CORE SCHEMA IN QUESTION FORMAT

CHARGE

1a) Charge Geometry: indicate on a figure of the situation at hand the sign(s) and, if appropriate, the magnitude and distribution of any and all charge(s), including any induced charges.

1b) Qualitative Description: Qualitatively, what approximate or actual charge configuration(s) can be substituted (if any) for the configuration depicted as a function of position either near to or far from (or within or on) the depicted situation? (This is closely related to 2b.)

1c) Quantitative Relations: What quantitative relationship(s) can you specify which determine the magnitude and/or density of the charge(s) in the situation before you? Give actual values, if possible, for charge(s) or charge densities in the situation.

ELECTRIC FIELD

2a) Lines of Force: Sketch enough lines of force to indicate the nature of the electric field for this situation. Indicate where each line begins and ends. Draw an arrowhead on each field line to indicate the direction of the field. Be sure that the strength of the electric field is represented by the spacing of the lines you draw. Identify anything that might be considered interesting about the lines; especially, any one region in the situation dominated by a particular set of lines.

2b) Qualitative Description: Describe qualitatively the nature of the electric field near to and far from (and possibly within or on) the object(s) depicted. Knowing the nature of the electric field some distance (near or far)

TABLE I (CONTINUED)

CORE SCHEMA IN QUESTION FORMAT

from the object(s) depicted, what geometry of object "appears" to be producing this field?

2c) Quantitative Relations: What quantitative relationship(s) can you state that specify the electric field for the various regions in space the situation tends to define (e.g., in, near, on, or far from the objects depicted)? Give actual values, if possible, for the electric field at points which you might consider "interesting" or important.

ELECTRIC POTENTIAL

3a) Equipotential Lines: Sketch enough equipotential lines to indicate qualitatively how the potential changes with respect to the object(s) at hand. Be sure that the spacing of your lines reflects equally-sized changes in electric potential. Identify interesting aspects of the equipotential lines; e.g., what shape are they, are they all the same shape, where does shape change, are they closed, etc.?

3b) Qualitative Description: Identify the location of the reference potential, V=0 volts, if necessary. Describe qualitatively the nature of the electric potential for every region implied by the situation, in particular, near to and far from (and possibly within or on) the object(s) depicted. Is the rate of change of potential constant or not in any given direction?

3c) Quantitative Relations: What quantitative relationship(s) can you state that specify the electric potential for every region implied by the situation. Give actual values, if possible, for the electric potential at points which you might consider interesting or important; e.g., points highlighted by the qualitative description.

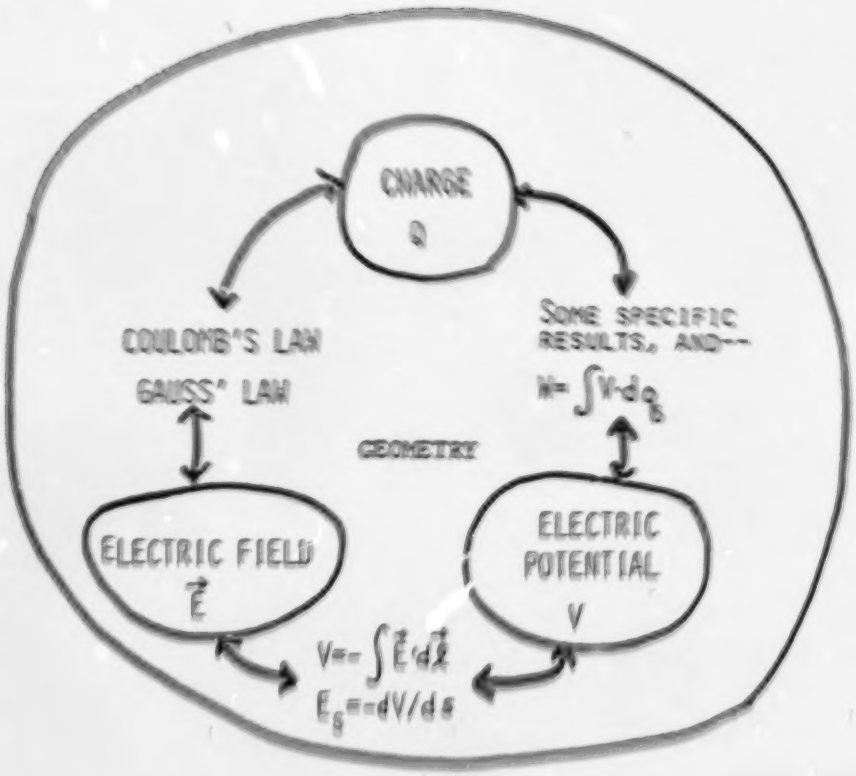

FIGURE 1

CONCEPTUAL MODEL OF ELECTROSTATICS

At the quantitative level, attention is focused on writing expressions which determine the actual values of the physical quantities charge, field, and potential as a function of position.

Description of the Procedures

Cognitive theory defines problem solving as understanding and search. The core schema stands in relationship to understanding as the concomitant procedural behaviors do to search: both are explicit formulations of the general cognitive theory in the context of electrostatics.

The procedural behaviors, presented in Table II, are seen as ways of completing the patterns initiated by the solver's initial representation of the problem statement.

Instructional Hypotheses

The main instructional hypothesis was a transfer of training hypothesis: if a student is given a declarative exposition of the core electrostatics schema and procedures which act upon it, and if this is combined with practice in use of the schema and concomitant procedures in open-ended situations without specified goals, then the student will show evidence of increased competency in solving "closed" problems (that is, where a goal is specified) in the core area of electrostatics.

The instruction was based on open-ended problems. It is through elaboration of this type of problem that a familiarity with the length and breadth of the core electrostatics schema may be experienced. For any given situation, the geometry and some statement regarding either

TABLE II

CONCOMITANT PROCEDURAL BEHAVIORS

THE TOPOLOGY OF SEARCH

General Behavior: Solvers may elaborate qualitative and quantitative aspects of the core schema in a variety of ways. Some possibilities:

1) A solely quantitative approach in one or in all three areas of the core schema.
2) A qualitative approach in one area, followed by a quantitative approach in that same area. This pattern is then repeated in another area.
3) A qualitative survey of all areas, followed by quantitative elaboration guided by the prior qualitative survey.

Preferred Habit: #3

CHECKING BEHAVIOR (ERROR DETECTION)

General Behavior: Solvers may or may not undertake to check any of their results, qualitative or quantitative. When checks are made, they are often of the following types:

1) Qualitative. Here, a quantitative relation is checked against qualitative understanding of the problem. For example, in the two point charge situation, it is known qualitatively that the field far from the charges is radial. A quantitative relation might have the field proportional to $1/r$, and not $1/r^2$ in the limit as r grows large. A radial field is proportional to $1/r^2$. Through this reasoning, therefore, an error is detected.

   Another important type of qualitative check involves judgments of reasonableness; e.g., a match between a particular quantitative result and "typical" values for that quantity in similar situations.

2) Quantitative. Here, numerical results are substituted back into relations which

produced them, providing a check of the algebra.

3) Dimensional analysis. This is the standard check of dimensional agreement between sides of an equation.

4) Consistency. Here, two independent lines of reasoning are used to arrive at the same result. Agreement between the two results boosts confidence in their veracity.

5) Reworking. Sometimes, checking means simply reworking a result.

Preferred Habit: Any of these behaviors is preferable to no checking at all. The most preferable habit is a liberal usage of all of these techniques.

SUMMARIZING AND APPLYING RESULTS

General Behavior: Like checking, this is a behavior that can be employed or can be ignored. When one summarizes, a point of reference in the developing argument is established. One summarizes after developing key results. This is like checking behavior, but a key difference is that in summarizing, one is looking for a feeling of completeness of an argument: Is anything left out? What else can be said? Am I going around in circles? Often, these questions are answered in terms of the application of the results derived: How can I use this information? What does this mean? Where do we go from here? Results are applied back to special cases or interesting cases. A result is generalized or specialized. A result may be matched against a qualitative statement.

Preferred Habit: Summarize! and apply results; avoid spending too much time going around in circles.

TABLE II (CONTINUED)

CONCOMITANT PROCEDURAL BEHAVIORS

QUALITATIVE REASONING

General--Behavior: Beyond the details of the qualitative core schema, one can reason qualitatively by (1) identifying cases, (2) making use of approximation, and (3) noting interesting facets of the situation at hand.

Preferred Habits:

1) Identify all applicable cases. If one case must be chosen to work with, choose it from alternatives. Having chosen a case, when summarizing, apply the result for this case to the other alternatives.

2) Specify idealizations which make the situation tractable. When summarizing, generalize results back to the reality underlying the idealization. Approximate results for use in qualitative checks.

3) Enumerate interesting facets of the situation at hand: novel, unique, or unexpected details.

QUANTITATIVE REASONING

General Behavior: (1) Quantitative relations are often cited by rote, and often re-derived; (2) coordinate systems are often employed; and, (3) graphs are sometimes drawn.

Preferred Habits:

1) Use remembered relations, but be sure that the variables involved are clearly and explicitly matched to the situation at hand, and that this match is meaningful and correct. This is best done by double checking the qualitative elaboration of the area of the core schema with which the relation deals. Obviously, when a relation is forgotten, it needs to be re-derived. Re-derivation can also serve as a final check.

TABLE II (CONTINUED)

CONCOMITANT PROCEDURAL BEHAVIORS

2) Do not employ a coordinate system until absolutly necessary. Take great care, when developing a coordinate system to (a) place its origin meaningfully, and (b) choose the most useful type of coordinate system (Cartesian, spherical, etc.).

3) Use graphs to show continuous changes of a quantity as a function of position. Develop a coordinate system for position prior to developing the graph. Graphs usefully relate regions of space.

charge distribution, field or potential, sufficiently determine the entire situation. The goal, then, for the instruction in open-ended problems, was to help students elaborate all inferences which could reasonably be drawn from a given situation.

While the instruction was based on open-ended problems, the instruction itself was by no means open-ended. A student was not given an open-ended situation and told: "Tell me everything you can!" On the contrary, the student was provided with explicit guidance in elaborating open-ended situations in the form of a specific representation and a specified set of procedures to manipulate that representation. Furthermore, the instructional treatment developed placed great emphasis on relating open-ended situations both to the specific closed problems which they subsume, and to a general representation for all core electrostatics situations: the core schema. This didactic provision of representation and process for open-ended elaboration distinguished our approach from discovery techniques of instruction.

Description of the Instruction

Students received direct expository explanation of the core schema and procedures, followed by practice in using these in a variety of open-ended problem situations. The treatment, applied to the typical lecture/recitation format of physics instruction, called for the exposition of the schema and procedures in lecture sessions; and for student practice on homework exercises, which was reinforced in recitation sessions.

The treatment designed replaced approximately one third of the total instructional time spent on electrostatics. The treatment was distributed throughout the span of that portion of a semester normally devoted to electrostatics, about three weeks.

The lecturer was provided with a set of overhead transparencies and accompanying narratives for each of three lectures. These were to be presented with little or no deviation or elaboration. Recitation leaders were provided with a lesson outline including a revised problem assignment syllabus indicating which problems were to be elaborated in an open-ended fashion and which were to be dropped from the normal syllabus to allow additional time.

The flow of instruction was designed to emphasize first the cognitive representation of electrostatics, then several useful procedures, and finally the application of this knowledge to a realistic everyday situation.

EXPERIMENTAL DESIGN

All subjects were enrolled in Physics 112 (second semester introductory physics, with calculus) at the University of Colorado, Boulder, Spring Semester, 1981. Physics 112 was structured into two identical lecture sessions, taught by the same lecturer. In addition to the weekly lecture sessions, each student in Physics 112 was assigned to one of 22 recitation sessions, all of which met once weekly, for one hour. It was arranged that recitation instructors taught one each of both experimental and control recitations, making recitation instructor

a crossed factor in the research design. The researcher was not involved in the delivery of any instruction, in lecture or in recitation.

Instruments and Measures

In recognition of the transfer nature of the study's hypothesis (e.g., experimental students are trained on open-ended problems yet tested on closed problems) the experimental design included a measure of pre-transfer performance. This instrument consisted of six questions, each of which presented a hypothetical problem solving situation with several alternative responses comprehensible to either group. The questions had no correct or incorrect answers. In the light of the problem solving theory upon which the treatment was based, one set of answers was suggested as correct. Using this measure it was posible to determine, at the level of comprehension in Bloom's Taxonomy (Bloom, 1956), the differentiation between the control and experimental groups with respect to comprehension of problem solving strategy.

The following question is one of the six used in this pre-transfer measure:

> "It is better to temporarily postpone the question posed in a electrostatics problem and make a few qualitative statements first, rather than tackling the question straight off. True or false?"

The principal measure of transfer of training from open to closed problems was a formal closed book hourly examination covering electrostatics, administered one week following the termination of the treatment. This examination provided measures for the following types

of performance: (1) qualitative multiple choice electrostatics questions; (b) closed, core problems; (c) closed, second order concept problems; (d) embedded problems involving kinematics; and (e) the total score on all problems combined.

A protocol analysis was designed to confirm whether any detectable differences in post-transfer performance (e.g., performance on closed problems) were due to application of the problem solving approach taught in the experimental treatment. Hence, a typical, but not trivial, closed electrostatic problem was designed and administered to ten students from each group, blocked by ability. Their thinking out loud protocols generated while solving the problem were analyzed using a coding form developed specifically to reflect those problem solving behaviors the treatment encouraged (see Table III).

At the end of the experiment, a brief affective questionnaire was administered to the students in the experimental recitations, which asked for student feelings on the usefulness of the lectures and special homework assignments.

The experimental design developed to test the main post-transfer hypothesis was a two factor mixed model ANCOVA: Group (fixed factor, two levels: control and experimental) X Recitation Instructor (random factor, three levels), with performance on the prior semester of physics chosen as covariate.

TABLE III

PROTOCOL CODING FORM

1) Diagram timing:

5---------4---------3---------2---------1---------0
EARLY NONE

2) Diagram quality:

5---------4---------3---------2---------1---------0
APPROPRIATE DETAIL POOR DETAIL NONE

3) Qualitative analysis precedes equation writing:

5---------4---------3---------2---------1---------0
DEFINITELY YES ABSOLUTELY NOT

4) Qualitative aspects explicitly mentioned:

a) YES NO spherical symmetry
b) YES NO all charge goes to outside of outer sphere
c) YES NO potential constant within outer surface of outer sphere
d) YES NO charge configuration is increasing its radius, so potential decreases proportionately

5) Is a plan or strategy for reaching the goal developed:

5---------4---------3---------2---------1---------0
APPROPRIATELY STATED AND EMPLOYED POORLY STATED NONE

6) Are the variables in any expression explicitly bound:

5---------4---------3---------2---------1---------0
DEFINITELY YES ABSOLUTELY NOT

7) Is there any consistent effort to confirm results:

5---------4---------3---------2---------1---------0
PROPERLY EXECUTED CHECKING NO CHECKING

8) At conclusion, how close at hand is any solution:

5---------4---------3---------2---------1---------0
A SOLUTION HAS BEEN REACHED (CORRECT OR NOT) NO SOLUTION NEAR

9) Has the correct solution been reached?

YES NO

10) Minutes required to terminate task: _____ min.

RESULTS

Observational Data

All lectures, experimental and control, were delivered by the same individual, a tenured professor on the physics faculty, at the University of Colorado, Boulder. In the experimental lectures, visual transparencies and accompanying narrative supplied to the lecturer were utilized as intended. Throughout the series of three lectures, a progression toward increasing emphasis on qualitative anlaysis in the control lectures occurred in spite of experimenter efforts to preserve treatment differentiation. However, the explicitness and organization of the experimental lectures, versus the implicitness and ad hoc flow of the control lectures, remained a major factor of treatment differentiation.

For the recitation instructors, student participation in the special experimental homework assignment (open-ended elaboration) was the principal source of treatment differentiation. No fundamental changes in approach in control recitation sections were observed over the course of the treatment.

Differences in recitation instructor style were observed. Instructor No. 1 was a first year graduate student. Much of the transitional behavior of graduate students relative to either novices or experts noted by Chi, Feltovich and Glaser (1980) was observed in this instructor. That is, conceptual focus seemed to be intermediary between surface appearance (naive representation) and deep structure (scientific representation).

Instructor No. 2, a tenured professor, had a very abstract style, rather brisk and intimidating. Tangential comments were tossed into the presentation, comments appropriate only for a much more mature audience. The instruction provided by Instructor No. 2 was accurate physics, but the presentation was heavily verbal, excluded gesturing, concrete manipulatives, or extensive use of analogy to students' prior experiences. Such phrases as "clearly" and "intuitively" were common.

Instructor No. 3, also a tenured professor, contrasted with the other two. This instructor has evolved an effective classroom manner, including the verbal involvement of students, and the use of manipulatives. A black film box was brought to both experimental and control sections to illustrate Gauss's Law (the box served as a Gaussian surface). His talks were enhanced with much physical movement, and his ideas were consistently related to normal experience; e.g., gravitation, skiing, Jacuzzis, the sensation of pressure, etc.

Regardless of their differences, none of the three instructors corrected homework in either treatment condition in a specific, detailed manner, which would provide individualized feedback to students. All homework was corrected at a very cursory level. All three instructors did explain the assigned experimental problems in class each week. However, reports from each instructor indicated that only half to one third of all experimental students made any attempt at the special homework assignments. Considerably fewer than that amount did a credible job on the assignments.

Pre-Transfer Measure

Student scores on the problem solving strategy test were analyzed using the design of the main analysis. In this analysis, ability was treated as a factor and not as a covariate. For the pre-transfer measure, treatment group was highly significant $F(1,83)=35.0$, ($p<.001$). No other main effect (e.g., instructor or ability) was statistically significant. There was no treatment group X instructor interaction.

Main Measure

Cell means (treatment group by ability by instructor) for the total score dependent variable are reproduced in Table IV; ANCOVA analysis of these data, in Table V.

Several significant effects for the instructor factor were produced. In each of these cases, Multiple Classification Analysis (Nie, et al., 1975) showed a consistent pattern of adjustment to the grand mean for the instructor effect, with one instructor consistently associated with a positive adjustment; another instructor with a negative effect; and a third instructor with an effect intermediate between these two extremes. No significant effects for treatment factor were found.

Protocol Study

The basic design of the main analysis was applied to the protocol scores with ability as a factor rather than as a covariate. No significant treatment effect was found. However, a significant ability effect was found, $F(2,15)=4.03$ ($p<.05$).

TABLE IV

CELL MEANS: TREATMENT GROUP BY ABILITY BY INSTRUCTOR FOR TOTAL SCORE ON ELECTROSTATICS EXAMINATION

DESCRIPTION OF SUBPOPULATIONS

CRITERION VARIABLE	ESSUBT	EXAM--ELECTROSTATICS TOTAL
BROKEN DOWN BY	TWOGROUP	MAIN EXPERIMENTAL GROUP
BY	PHY111	ABILITY BASED ON PHY111 FINAL GRADE
BY	TEACHER	RECITATION TEACHER

VARIABLE	CODE	VALUE LABEL	SUM	MEAN	STD DEV	VARIANCE	N
FOR ENTIRE POPULATION			5557.0000	50.0631	13.1897	173.9687	(111)
TWOGROUP	1	SEGREGATED CONTROL	3129.0000	53.0339	12.0573	145.3781	(59)
PHY111	1	LOW THIRD	616.0000	44.0000	12.6187	159.2308	(14)
TEACHER	1	TEACHER NO. 1	96.0000	48.0000	12.7279	162.0000	(2)
TEACHER	2	TEACHER NO. 2	215.0000	35.8333	10.9072	118.9667	(6)
TEACHER	3	TEACHER NO. 3	305.0000	50.8333	10.9621	120.1667	(6)
PHY111	2	MIDDLE THIRD	697.0000	46.4667	7.2493	52.5524	(15)
TEACHER	1	TEACHER NO. 1	337.0000	48.1429	6.5936	43.4762	(7)
TEACHER	2	TEACHER NO. 2	129.0000	43.0000	5.5678	31.0000	(3)
TEACHER	3	TEACHER NO. 3	231.0000	46.2000	9.4446	89.2000	(5)
PHY111	3	HIGH THIRD	1816.0000	60.5333	8.6093	74.1195	(30)
TEACHER	1	TEACHER NO. 1	536.0000	59.5556	8.2175	67.5278	(9)
TEACHER	2	TEACHER NO. 2	457.0000	57.1250	11.9096	141.8393	(8)
TEACHER	3	TEACHER NO. 3	823.0000	63.3077	5.8791	34.5641	(13)
TWOGROUP	2	SEGREGATED EXPERMNTL	2428.0000	46.6923	13.7149	188.0995	(52)
PHY111	1	LOW THIRD	685.0000	36.0526	12.0852	146.0526	(19)
TEACHER	1	TEACHER NO. 1	294.0000	36.7500	15.4896	239.9286	(8)
TEACHER	2	TEACHER NO. 2	106.0000	26.5000	6.6583	44.3333	(4)
TEACHER	3	TEACHER NO. 3	285.0000	40.7143	7.0170	49.2381	(7)
PHY111	2	MIDDLE THIRD	1086.0000	49.3636	9.9405	98.8139	(22)
TEACHER	1	TEACHER NO. 1	406.0000	50.7500	12.3607	152.7857	(8)
TEACHER	2	TEACHER NO. 2	326.0000	46.5714	10.7526	115.6190	(7)
TEACHER	3	TEACHER NO. 3	354.0000	50.5714	6.2144	38.6190	(7)
PHY111	3	HIGH THIRD	657.0000	59.7273	8.4391	71.2182	(11)
TEACHER	1	TEACHER NO. 1	116.0000	58.0000	19.7990	392.0000	(2)
TEACHER	2	TEACHER NO. 2	237.0000	59.2500	6.1305	37.5833	(4)
TEACHER	3	TEACHER NO. 3	304.0000	60.8000	6.9785	48.7000	(5)

TABLE V

ANCOVA TABLE AND MULTIPLE CLASSIFICATION ANALYSIS
FOR TOTAL SCORE ON ELECTROSTATICS EXAMINATION

* * * * * * * * A N A L Y S I S O F V A R I A N C E * * * * * * * *

E3SUBT EXAM--ELECTROSTATICS TOTAL
BY TWOGROUP MAIN EXPERIMENTAL GROUP
TEACHER RECITATION TEACHER
WITH PHY111N PHY111N FINAL SCORE

SOURCE OF VARIATION	SUM OF SQUARES	DF	MEAN SQUARE	F	SIGNIF OF F
COVARIATES	10002.128	1	10002.128	122.030	.001
PHY111N	10002.128	1	10002.128	122.030	.001
MAIN EFFECTS	780.964	3	260.321	3.176	.027
TWOGROUP	33.678	1	33.678	.413	.522
TEACHER	735.829	2	367.914	4.489	.013
2-WAY INTERACTIONS	35.823	2	17.911	.219	.804
TWOGROUP TEACHER	35.823	2	17.911	.219	.804
EXPLAINED	10818.915	6	1803.152	21.999	.001
RESIDUAL	8688.218	106	81.964		
TOTAL	19507.133	112	174.171		

138 CASES WERE PROCESSED.
25 CASES (18.1 PCT) WERE MISSING.

* * M U L T I P L E C L A S S I F I C A T I O N A N A L Y S I S * *

E3SUBT EXAM--ELECTROSTATICS TOTAL
BY TWOGROUP MAIN EXPERIMENTAL GROUP
TEACHER RECITATION TEACHER
WITH PHY111N PHY111N FINAL SCORE

GRAND MEAN = 49.84

VARIABLE + CATEGORY	N	UNADJUSTED DEV'N	UNADJUSTED ETA	ADJUSTED FOR INDEPENDENTS DEV'N	ADJUSTED FOR INDEPENDENTS BETA	ADJUSTED FOR INDEPENDENTS + COVARIATES DEV'N	ADJUSTED FOR INDEPENDENTS + COVARIATES BETA
TWOGROUP							
1 SEGREGATED CONTROL	60	2.84				.53	
2 SEGREGATED EXPERMNTL	53	-3.22				-.60	
			.23				.04
TEACHER							
1 TEACHER NO. 1	36	-.26				.16	
2 TEACHER NO. 2	33	-3.99				-3.65	
3 TEACHER NO. 3	44	3.20				2.60	
			.22				.19
MULTIPLE R SQUARED							.553
MULTIPLE R							.743

Affective Questionnaire

Two multiple choice affective questions were presented to experimental students following the treatment. A majority (60 percent) of students felt that the special homework assignments were slightly helpful to them in understanding electrostatics. Forty-eight percent of the students responded that they felt the experimental lectures were slightly helpful, with 21 percent feeling they were harmful and 23 percent feeling they were very helpful.

DISCUSSION OF RESULTS

Content Validity

The discrepancy between the positive results on the pre-transfer measure and the negative results on the main measure indicate that knowing that certain behaviors are desirable did not transfer into a knowledge of how to use these behaviors.

For the pre-transfer measure, it is important to note that there was no main effect for instructor. This indicated that instructor style, no matter how naturally similar to the experimental treatment, did not result in the induction in the students of an explicit and conscious awareness of the substance of the experimental treatment.

Even given the null result of the main measure, evidence can be cited supporting the hypotheses that: (a) the specific model of problem solving skill in electrostatics developed is valid; and, (b) the principal explanation for the absence of a treatment effect lies in the weakness of the treatment delivery.

Consider the presence of a main effect for instructor. This effect was not only consistent across several dependent variables, but the ranking of the instructor benefit was also consistent. Insturctor No. 3's students consistently performed better than Instructor No. 1's students, who in turn, consistently out performed Instructor No. 2's. While there may be numerous explanations for this effect, the differences in instructor style previously noted provide a reasonable explanation for why one instructor did so much better than another. The differences in instructor effectiveness directly parallel differences in style reflecting the substance of the treatment. The presence of such a parallel argues for the validity of the problem solving model presented.

In further support of the validity of the model upon which the experimental treatment was based, consider the results of the protocol study. The protocol scores derived were based on a coding format explicitly founded on the substance of the treatment. The protocol scores indicated the extent to which a student was behaving in consonance with the treatment. No effect for treatment group was noted. However, there was an effect for ability. This suggests that abler students induced, on their own, the type of behavior that the treatment attempted to teach, while less able students did not.

In summary, data of the instructional experiment, in the parallels between the effect for instructor in the main measure and the effect for ability in the protocol study, argues that the explicit basis of the instruction developed has the same substance which (a) when employed implicitly yields an advantage to a particular instructional

style, and (b) was noted in abler students, whether a problem was answered correctly or not. Hence, it is argued that the content of the instruction provided has validity because it successfully embodies features which do indeed bring about or account for improved problem solving performance.

Treatment Strength

Having argued for content validity, the issue of the effectiveness of the treatment must be contemplated. The data show no effect for treatment. This result must stem from weak application or design of the treatment, because an argument cannot be made for an inherent lack of content validity. A lack of treatment strength can be seen in the specifics of the study.

The instructional environment of this study was taken as a given constraint. A choice was made to attempt this instructional intervention in the natural context of established instructional practice in a large university level physics course. On one hand, this was done in order to have a large enough sample size to support the statistical power of the study. On the other hand, it was felt that this was a good place to start, because success here would result in immediate benefit to established instructional practice.

This study inherits one glaring weakness from standard practice in this particular course: the policy of not providing detailed feedback on student homework assignments. This was a matter of economics, not of oversight. To have insisted on an exception to this policy for the

special homework assignments would have placed an intolerable burden upon the participating instructors.

The lack of feedback and effective practice may be the best explanation of why the problem solving comprehension advantage of the experimental students did not transfer to an advantage in problem solving skill.

This lack of feedback is in stark contrast to two previous studies of problem solving instruction in physics which did find effects favoring the treatment. These two studies (Larkin, 1975; 1977) relied on intense individualization. Indeed, Larkin (1975) emphasized the need for this intensity of treatment. The present study attempted to apply the theory in a much more traditional setting. The negative results, in the light of these two studies, seem especially interpretable as a lack of treatment strength.

Choice of Electrostatics

A major reason for the choice of electrostatics was that there is no layman's physics for this topic. One of the difficulties of teaching kinematics is in overcoming student preconceptions about the notions of mass, weight, momentum, and force. Electrostatics was chosen in order to avoid these difficulties.

However, the very lack of a naive representation for electrostatics might help explain why there was no main effect for treatment. The reasoning can be described in the following manner. In the studies of kinematics problem solving novices are able to solve

these problem types, but do so in a fundamentally different way than do experts. Novices employ a naive representation of the problems at hand. This leads to difficulties for novices in places where the naive representation provides no useful parallel to an essential scientific construct. Students have trouble with the superposition of forces, as noted, because they are looking at bodies (blocks, etc.) and not at force diagrams or conservation principles, as do experts.

In the case of electrostatics, it can be argued, students do not solve problems at all well because they have no naive representation upon which to rely. In this case, their only recourse, lacking a mature scientific representation, is a means-ends attack on the mathematical representation. Of course, this does not work well.

Electrostatics is too complex to have an equation for every possible situation, and the only route to the understanding which is required in order to generate a meaningful set of equations is through the appropriate scientific representation. The lack of strength of treatment, therefore, may be accountable by a "floor effect" resultant from the novice's lack of a familiar naive representation for electrostatics.

RETROSPECTIVE CRITIQUE

In retrospect, a better environment could have been chosen to test the effectiveness of instruction based on the explicit domain-specific model of problem solving developed. The environment chosen was the traditional large group lecture/recitation. This format is a very

difficult one in which to conduct research, due to all of the uncontrollable variables it introduces. For example, in this study, treatment differentiation was difficult to maintain. Also, it was nearly impossible to assure a given level of the power of either treatment condition because detailed feedback to students was precluded. It would be a much better idea to test this instruction in a more controlled environment, for example a one-on-one tutorial situation.

This study was conducted as a preliminary phase of the development of a series of computer assisted problem solving lessons. Since such lessons are inherently individualized instruction, the one-on-one approach to pilot testing the instruction would have been more appropriate than the group approach taken.

In a one-on-one instructional environment, much greater latitude would be available for exploring instructional techniques. The study performed is significant in that it has identified a model of expertise upon which to base instruction: the core schema (Figure 1 or Table I), and the set of related procedures (Table II). A model of expertise is not equivalent to a model for instruction, but it does provide a basis for explicit instruction in how to solve problems.

The study performed is also significant in that it has identified and developed some possible instructional strategies to use this basis. These instructional strategies can be further developed and tested in a tutorial environment. These strategies include: the use of a visual mnemonic of the core schema, a list of questions to guide qualitative elaboration of the core schema for a given problem, the

technique of using open-ended questions as a point of departure for making such elaborations, and the set of procedures which provide guidance in the various steps of problem solving (from making a diagram through checking the solution). With a suitable methodology, a greater degree of sophistication in instructional design, based on the underlying model of expertise, could be developed for problem solving tutorials than was possible for the group lecture mode.

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